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THRUST MEASUREMENTS OF A COMPLETE AXISYMMETRIC SCRAMJET IN AN IMPULSE FACILITY

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ABSTRACT

This paper describes tests which where conducted in the hypersonic impulse facility T4 on a fully integrated axisymmetric scramjet configuration. In these tests the net force on the scramjet vehicle was measured using a deconvolution force balance. This measurement technique and its application to a complex model such as the scramjet are discussed. Results are presented for the scramjet's aerodynamic drag and the net force on the scramjet when fuel is injected into the combustion chambers. It is shown that a scramjet using a hydrogen-silane fuel produces greater thrust than its aerodynamic drag at flight speeds equivalent to 2600 m/s.

INTRODUCTION

Extensive investigations, both numerical and experimental, have been conducted to determine if scramjets produce sufficient thrust to be economically viable for hypersonic flight. Although these investigations are important, the most definitive way to determine the viability of a scramjet is to perform flight tests with a fully integrated configuration. That is to say, flight tests of a scramjet with intakes, combustion chambers, thrust surfaces and exterior surfaces.

Flight tests can be made in two ways. A scramjet could be propelled through the atmosphere with a suitable carrier or alternatively, and what was used for the tests described here, flight tests can be performed in a hypersonic test facility.

The free piston driven shock tunnel T4 was used to test the axisymmetric scramjet seen in figure 1. The drag or net thrust produced by the scramjet was obtained using a deconvolution force balance (Sanderson and Simmons (1991)). The time-history of the force acting on the scramjet is obtained by numerically deconvolving measurements made of the axial strain in a sting attached to the scramjet.

This type of balance was originally designed so that a force could be deconvolved over a period of approximately 1 ms. However, this is insufficient for testing scramjets. An increase in deconvolution time is required because valves are opened and fuel is injected prior to the start of the test flow. To obtain an accurate time history of the force on the scramjet these events must also be deconvolved. The development of this balance and technique to the point where time-history measurements can be made over a period in excess of 10 ms on a complicated model has been crucial to the measurement of the net thrust produced by a scramjet.

The ability to measure the overall performance of a fully integrated scramjet is one which should enhance the design efforts towards the development of this type of engine. The results presented here are the first record of the thrust produced by a fully integrated scramjet which has been tested in an impulse facility.

MODEL DESCRIPTION

A schematic of the scramjet, fuel tank and sting is shown in figure 1. The scramjet is connected to the fuel tank which in tern is connected to the sting. The scramjet is cylindrical in shape with a conical forebody and thrust surface. It has an aluminum centrebody and a stainless steel cowl. The fuel tank is cylindrical in shape and is made from stainless steel. The sting is a brass cylindrical pipe. Semiconductor strain gauges are attached to the sting approximately 200 mm downstream of the fuel tank.

The sting and model are suspended by fine threads so that the combination is free to move in the direction of the axis of the tunnel. The fuel tank and sting are shielded from the test flow. This shielding is required to ensure that the forces which are measured are only the aerodynamic forces acting on the model.

The overall length of the scramjet is 274 mm and its external diameter is 71 mm. The conical forebody has a 9 degree half angle and the thrust surface has a 11 degree half angle.

Six identical combustion chambers are distributed

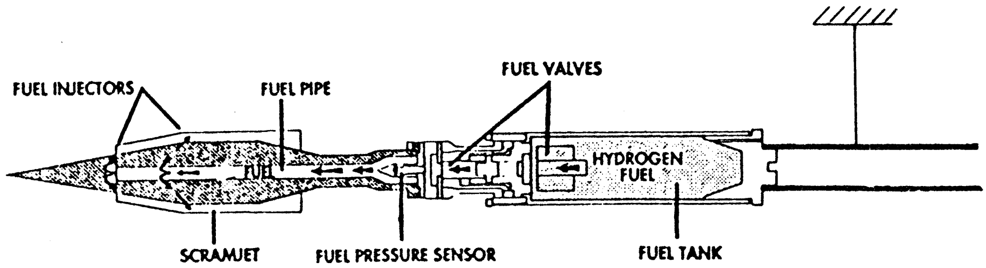

Figure 1. Schematic of the scramjet and its fuel tank.

around the cylindrical centrebody. The combustion chambers are 58.5 mm long and of constant cross-section. The centrebody is cylindrical with a diameter of 51 mm.
A connecting pipe between the model and the fuel tank is 75 mm long. The fuel tank shielding which seals on this pipe starts 55 mm downstream of the end of the thrust surface. Aerodynamic drag on this 55 mm section constitutes part of the drag on the scramjet.
Fuel could be injected upstream of the combustion chamber intakes from injectors located on the conical forebody or from injectors within the intakes positioned at the entrance to the combustion chambers. In the tests described here, fuel was injected only from the injectors located at the entrance to the combustion chambers. The upstream injectors were plugged.
In each combustion chamber there is one injector. Each injector is a 2mm orifice angled at 30 degrees to the centreline of the scramjet and located centrally at the entrance to the combustion chamber. Fuel is supplied to the injectors from the fuel tank by means of a pipe through the centrebody of the scramjet.
The fuel pressure is monitored in the fuel pipe as shown in figure 1. This pressure and calibration factors for the injectors are used to determine the mass flow rate of the fuel. It is assumed that the flow through the injectors is choked. The mass flow rate of the fuel is varied by changing filling pressure of the fuel tank.
Fuel flow is controlled by a fast acting valve located between the scramjet and the fuel tank. The valve fully opens in approximately 6 ms (depending on filling pressure) and closes in approximately 100 ms.

THE FORCE MEASUREMENT TECHNIQUE

The force balance used to measure the scramjet's thrust is described in detail by Sanderson and Simmons (1991) and involves determining the time-history of the force acting on the test model by monitoring the axial strain on a long sting attached to the base of the model. When the flow starts around the model the resulting aerodynamic forces cause stress waves to propagate and reflect within the model and fuel tank. These waves are transmitted into the sting and are monitored by the strain gauges. Such a system can be modelled as a linear system characterized by an input $u(t)$ - the axial force on the model, an output $y(t)$ - the strain measured in the sting and an impulse response $g(t)$ relating the two. This can be written using a convolution integral,

$$y(t) = \int_0^t g(t-\tau)\, u(\tau)\, d\tau. \qquad (1)$$

When the impulse response and the output are known, deconvolution techniques can be used to solve the inverse problem to find the time-history of the axial force on the model.
The impulse response which characterizes the system can be found either experimentally or by using dynamic finite element analysis. For the present tests an experimentally determined impulse response has been used. This was found by suspending the model and sting by a fine wire attached to the tip of the conical forebody of the scramjet. The wire was then cut close to the tip of the forebody to produce a sudden removal of a tensile load. This is equivalent to a step-like drag load applied at the tip of the model. The resulting strain gauge output (figure 2) measured in the sting gives the step response for the system. The impulse response is then found by differentiating the step response with respect to time.
The opening of the fuel valve a few milliseconds before the arrival of the test flow added some complications to the force balance measurement technique not previously encountered. Previously (Sanderson and Simmons (1991)) strain gauge signals

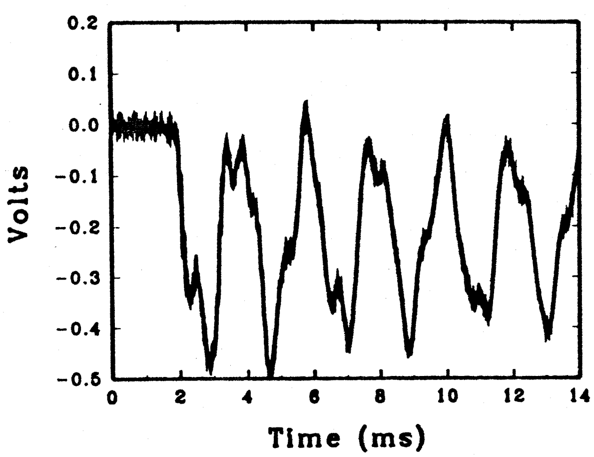

Figure 2. Strain gauge output as a function of time for a unit step load applied to the scramjet nose.

had only been processed to the point in time at which waves that reflected from the downstream end of the sting returned to the measurement location. However, it was found in the work of Porter et.al. (1993) that signals could be processed beyond this time provided that an impulse response was used which included characterization of these reflected waves. Since the opening of the fuel valves causes an output on the strain gauge signal it became imperative in the present tests that signals could be deconvolved through a number of stress wave reflections.

FUEL DESCRIPTION

Initially, hydrogen was used as the fuel, however, it was observed that very little thrust was obtained. It is believed that the combustion chambers are too short for the fuel to fully combust at the conditions targeted. To reduce the combustion length, silane (SiH_4) was added to the hydrogen. 13% of the fuel's volume was silane. Fuel was injected at an equivalence ratio of 0.8.

A typical record of the fuel pressure is given in figure 3. It can be seen that the fuel pressure is constant during the test time. The fuel pressure remains constant for approximately 3 ms, after which it falls rapidly as the fuel is drained from the fuel tank. It is critical that the fuel valve is opened so that this 3 ms period is coincident with the test flow. Ideally, the fuel pressure should reach its maximum approximately 0.5 ms before the test flow arrives. If fuel is injected early then the mass flow rate of the fuel will not be steady and furthermore, the time-history of the strain induced into the sting from the injection of fuel may not be fully recorded or will be excessively long. Consequently, the force on the scramjet could not be properly deconvolved.

RESULTS

Figures 3, 4, 5 and 6 display the measurements made during the tests. Time t=0 on all figures represents the same time during the tests. The flow arrives at the test section at t = 0.5 ms.

FLOW PROPERTIES

In the operation of a reflected shock tunnel the test gas is first shock heated and is then expanded through a contoured nozzle. The temperature of the test gas after it is heated but before it is expanded is determined using ESTC (McIntosh (1968)) to be 2700 K. Properties of the test gas in the test section are then determined using NENZF (Lordi et.al. (1966)). In the experiments described here it is assume that the test gas is in chemical equilibrium as it expands down the nozzle. It has been determined that, in the test section, the test gas has a velocity of 2400 m/s, a density of 0.09 kg/m^3, and a temperature of 350 K. The total enthalpy of the flow is 3.3 MJ/kg and therefore is equivalent to a flight speed of 2600 m/s.

Figure 4 displays measurements made of the static and Pitot pressures. It can be seen that the test flow establishes itself approximately 0.5 ms after the arrival of the first shock. Subsequently, the flow is quasi-steady for approximately 1.5 ms.

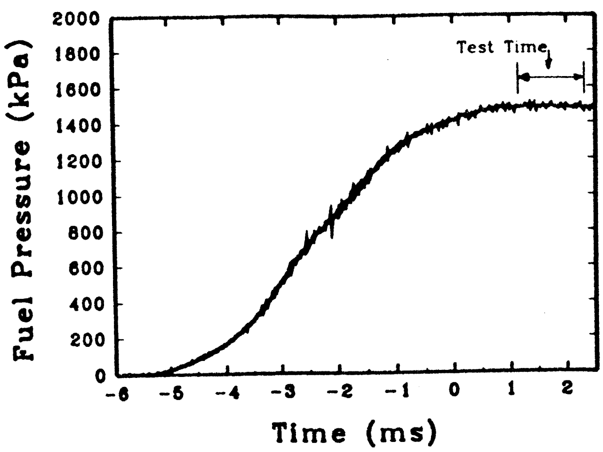

Figure 3. Fuel pressure as a function of time.

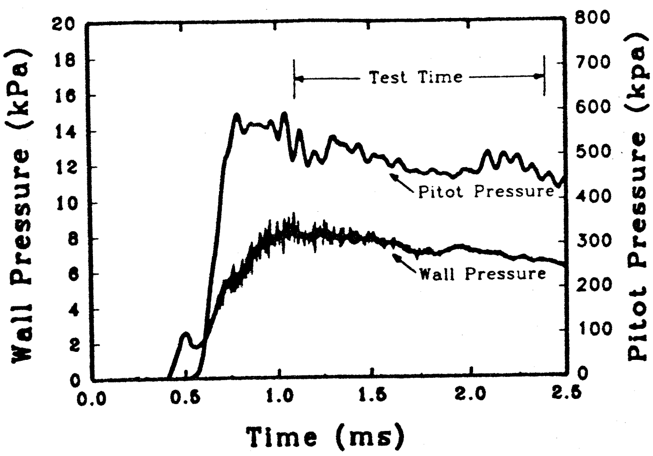

Figure 4. Wall and Pitot pressure as a function of time.

FORCE MEASUREMENTS

Figure 5 displays the output from the strain gauge mounted on the sting. The thrust produced by the injection of the fuel is observed as a relatively slow oscillation prior to the arrival of the test gas. When the test flow arrives it can be observed that the output is more complex.

The output in Figure 5 is deconvolved using the unit impulse response function to obtain the time-history of the net force on the scramjet. The result of this deconvolution is displayed in Figure 6.

Figure 6 displays three such deconvolved time-histories. These are the net forces on the scramjet when

(i) fuel is injected into a test gas of air,

(ii) fuel is injected into a test gas of nitrogen and

(iii) fuel is not injected and the test gas is air.

In the latter case it can be seen that the scramjet experiences a drag-history which basically reflects the slight decay observed in the Pitot pressure (figure 4). It can be seen that the drag is

approximately 140±25 N.
When nitrogen is used as a test gas and fuel is injected the drag on the scramjet is approximately 90±20 N. Hence, the drag is approximately 50 N less than the fuel off test in air. There is a slight difference in flow conditions between the air and nitrogen test gases, however, the drag is reduced primarily due to the presence of the fuel. When fuel is injected, it can be seen, prior to the arrival of the test flow, that the fuel induces a thrust of approximately 30 N. It is speculated that the the remaining 20 N reduction in drag results from the different test gases and fuel air interactions which possibly change the skin friction coefficients within the combustion chambers.
Figure 5 also displays the drag and thrust on the scramjet when fuel is injected into air. It can be seen, as above, that prior to the test flow the fuel induces a net thrust of approximately 30 N. As the flow establishes itself across the model the drag increases, following closely the result obtained with the nitrogen test gas. However, once the flow is established ignition of the fuel occurs and the drag is substantially reduced. 200 μs after flow establishment the thrust created by the combustion of the fuel is sufficient to balance the drag. 1 ms after flow establishment and during the test time the net thrust is approximately 50 N. During the test time the net thrust peeks at approximately 95 N and is always greater than 40 N.

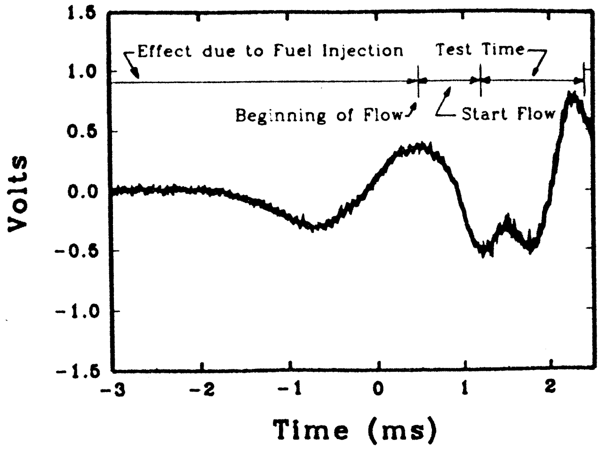

Figure 5. Strain gauge output as a function of time. Fuel injected into air

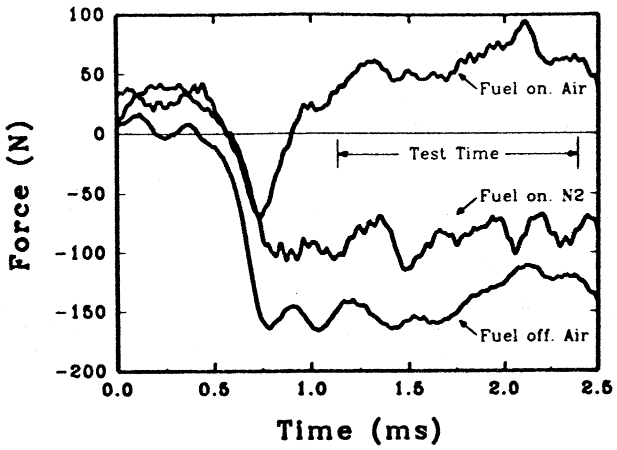

Figure 6. Net force on the scramjet as a function of time when fuel is injected into air and nitrogen test gases and when fuel is not injected and the test gas is air.

CONCLUSIONS

The impulsive force balance and the deconvolution techniques described in this paper are sufficiently advanced to measure the net force on a complicated model.
The use of an experimentally determined unit impulse response function has made it possible to determine with good frequency response the net force time-history on a model such as the scramjet, where the time-history of the forces applied to the model are of the order of 10 ms.
The scramjet used in these tests, although producing more thrust than drag, will need to be more efficient to become viable. The technique described above has made it possible to test new designs in hypersonic impulse facilities. Thus, definitive values for overall performance of scramjet designs can now be obtained relatively simply and cheaply at hypersonic conditions.

ACKNOWLEDGEMENTS

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